

Supplementary Materials

Predicting when and where climate change becomes robustly detectable

Supplementary note

Physical interpretation of regional differences in climate recoverability

Regional differences in climate recoverability ultimately reflect spatial variations in the local signal-to-noise ratio. To investigate the physical origin of variations in the forced component of this ratio, we compare historical precipitation responses with DAMIP single-forcing simulations driven by greenhouse gases (GHG), anthropogenic aerosols (AER) and natural forcing (NAT) (Supplementary Figs. 1 and 2). The correspondence between historical all-forcing responses and individual forcing experiments exhibits pronounced geographical variations (Fig. 4a,b). In many regions, historical precipitation changes closely resemble the response to a single forcing, whereas elsewhere no dominant forcing emerges because multiple forcings contribute similarly, in opposite direction, or internal variability obscures the forced signal. Greenhouse gases provide the dominant correspondence over much of the globe, while aerosol and natural forcing become relatively more important in regions characterized by greater spatial heterogeneity (Supplementary Fig. 2b).

Across all grid points, the sampling required to recover the forced response decreases monotonically with the maximum correspondence between the historical response and any single-forcing experiment (Supplementary Fig. 2c). Regions whose historical evolution is more strongly explained by a coherent forcing require fewer realizations, whereas regions exhibiting weaker forcing correspondence require progressively larger ensembles. Consistent with this interpretation, regions dominated by greenhouse-gas forcing generally require few realizations, whereas those dominated by aerosol- and natural-forcing regimes require larger ensembles (Supplementary Fig. 2d), reflecting the smoother spatial structure of greenhouse-gas responses compared with the more heterogeneous aerosol forcing and weaker natural-forcing signals.

Previous studies have shown that internally-generated circulation variability represents a major source of uncertainty in regional climate change¹⁻³, while heterogeneous aerosol forcing contributes substantially to regional hydroclimatic differences⁴⁻⁷. Our contribution is to show how these established physical controls are translated into regional climate recoverability through the local SNR. Recoverability therefore provides a quantitative bridge between the physical processes governing regional climate change and the sampling required to robustly recover their externally forced responses. Here, these established physical controls are linked quantitatively to recoverability through their influence on the local SNR.

Supplementary figures

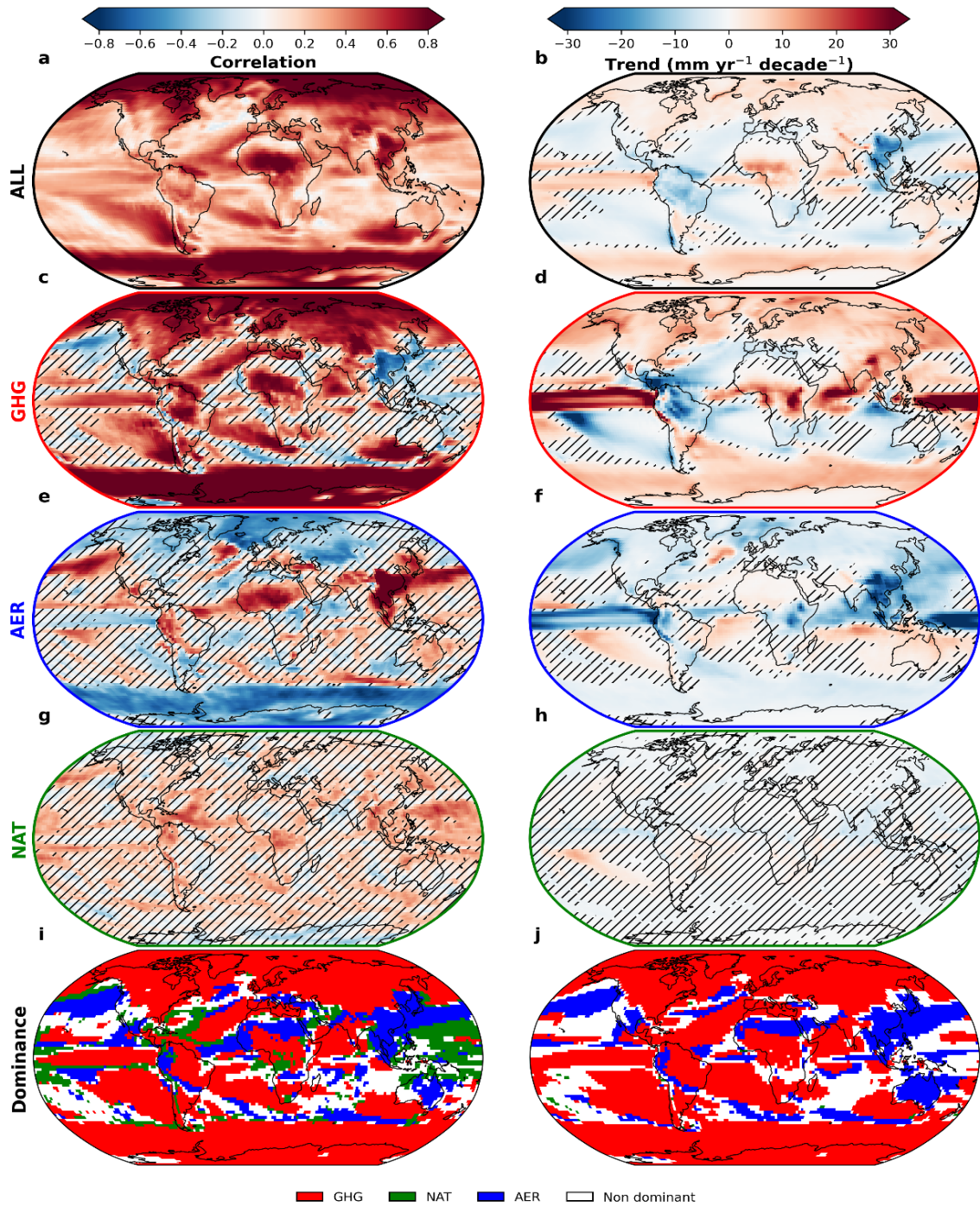


Figure 1 Single-forcing contributions to regional climate recoverability over 1940-2014.

(a) Same as main Fig 1b. (c, e and g) Spatial correlations between the ALL (782 historical members) response and ensemble-mean DAMIP responses to GHG, AER and NAT forcings. Stippling indicates non-significant correlations ($p \geq 0.05$). (i) Dominant forcing inferred from the strongest positive significant correlation. White areas indicate locations where all correlations are either non-significant or negative. (b, d, f and h) Ensemble-mean precipitation trends for ALL, GHG, AER and NAT simulations. Stippling indicates non-significant trends ($p \geq 0.05$). (j) Dominant forcing contribution, defined as the largest significant trend having the same sign as the ALL response. White areas indicate locations where the ALL trend is not significant or where no individual forcing exhibits a significant trend consistent with the ALL response.

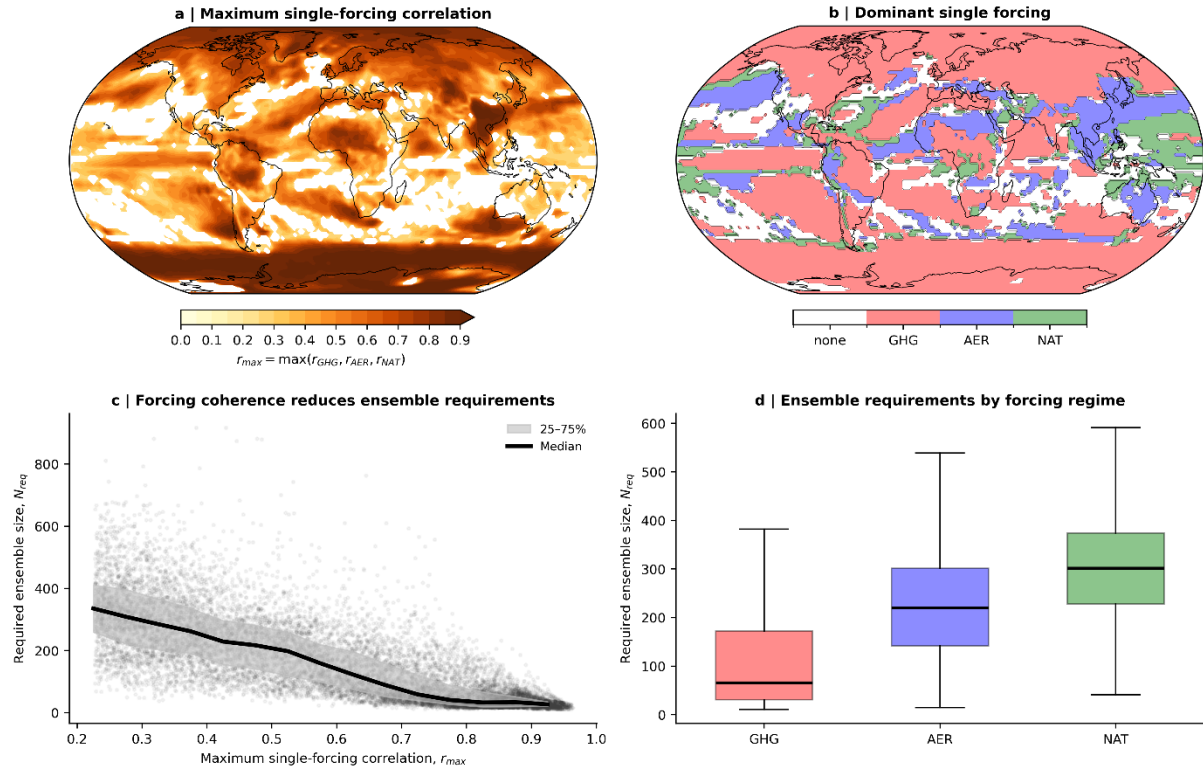


Figure 2 Physical origins of regional climate recoverability. a) Maximum statistically significant correlation ($r_{\max}$) between historical all-forcing precipitation responses and the three DAMIP single-forcing responses. b) Dominant forcing associated with $r_{\max}$. Colours identify the forcing (greenhouse gases, GHG; anthropogenic aerosols, AER; or natural forcing, NAT) producing the strongest significant correspondence with the historical all-forcing response. c) Relationship between the required ensemble size (N_{req}) and $r_{\max}$. The black curve shows the median response and the grey shading the interquartile range. Regions exhibiting stronger correspondence between historical and single-forcing responses require substantially fewer realizations to recover coherent forced responses. d) Distribution of N_{opt} for regions where GHG, AER or NAT forcing provides the strongest significant correspondence with the historical response. Regions dominated by greenhouse-gas forcing generally require fewer realizations than regions dominated by aerosol forcing, whereas natural forcing is associated with the largest sampling requirements. Together, the four panels show that the geography of regional climate recoverability is controlled not only by internally generated variability but also by the spatial coherence of externally forced climate responses.

References

1. Deser, C., Knutti, R., Solomon, S. & Phillips, A. S. Communication of the role of natural variability in future North American climate. *Nature Clim Change* **2**, 775–779 (2012).
2. Shepherd, T. G. Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geosci* **7**, 703–708 (2014).
3. Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021: Water Cycle Changes. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1055–1210, doi: 10.1017/9781009157896.010. in.
4. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021). doi:10.1017/9781009157896.
5. Gillett, N. P., Zwiers, F. W., Weaver, A. J. & Stott, P. A. Detection of human influence on sea-level pressure. *Nature* **422**, 292–294 (2003).
6. Zhao, C. *et al.* Observational evidence and mechanisms of aerosol effects on precipitation. *Science Bulletin* **69**, 1569–1580 (2024).
7. Rosenfeld, D. *et al.* Global observations of aerosol-cloud-precipitation-climate interactions. *Reviews of Geophysics* **52**, 750–808 (2014).